

On the Similarities between Radiation and Mechanical Strains

"On the Similarities between Radiation and Mechanical Strains," By JAGADIS CHUNDER BOSE. Communicated by LORD RAYLEIGH, F.R.S. Received April 18,—Read June 20, 1901.

I have in the previous paper described the various interesting effects due to visible and electric radiation.

Different considerations were adduced which tended to show that these effects were due to molecular strain, produced in the substance by the action of radiation. The whole history of the change produced by radiation—both the direct and after-effects—was graphically recorded in the various curves given. It was supposed that the strain effect on a substance was attended with conductivity or electromotive variation. This supposition can be further verified by observing whether undoubted strain, which can be produced by mechanical means, does give rise to a conductivity or electromotive variation.

As regards the conductivity variation due to mechanical strain, it is well known that in the construction of standard resistance coils the effect of winding the wire on a spool is to produce a distinct variation of resistance, and that this strain effect can only be removed by annealing. The difference between the resistance of a substance when strained and after it is annealed is sometimes very considerable.

The effect of electric radiation is very great in changing the conductivity of a mass of discontinuous particles. It is to be borne in mind that the effect of electric radiation is only skin-deep. As the action is one of surface, the larger the surface the greater is the effect produced. We see that in loose particles the effective surface accessible to radiation is very much enlarged. Moreover, the resistance offered to the particles is not due to the individual solid lumps, but to the resistance of *surface* layer. It is precisely the surface layers that are affected by radiation, and hence the marked variation of resistance.

When the particles become continuous, the radiation can only affect the extremely thin layer of molecules on the surface, the mass in the interior being shielded by the outer conducting sheet; the molecular changes produced on the surface layer do not affect to any appreciable extent the conductivity of the mass.

For detection of strain effect in continuous solids the method of electromotive variation is more suitable. We have seen that light causes a P.D. between the acted and unacted plate. We shall employ this method to find out whether mechanical disturbance gives rise to a similar electromotive variation between the acted and unacted plate.

1. The Strain Cell.

For the purpose of the experiment, I made a voltaic element composed of two pieces of the same metal wire, $W.W'$, cut from the same length. These are fixed parallel to each other in an L-shaped piece of ebonite, see fig. 11. The upper ends of the wires are in connection with the electrodes EE' , which lead to a very sensitive dead-beat galvanometer of D'Arsonval type. The wires at their lower ends are fixed to the ebonite piece by means of ebonite screws SS' . The upper ends, as has been said, are fixed to metallic rods EE' (which also serve as the electrodes), kept moderately stretched by springs CC' . A long handle, A , provided with a pointer, could be attached either to E or E' , and, by its means either of the wires could be twisted. The angle of the twist is measured with the help of a graduated circle, not shown in the figure.

If a cell be made of two clean wires cut from the same piece, with water as the electrolyte, there should theoretically be no P.D. between the two. But in practice there is found a small P.D. between the wires, owing to small difference in the molecular condition.

But this initial difference can be annulled by appropriate means. One method is to stretch one of the two wires by which the initial difference may be neutralised. The particular wire which should be stretched is found by trial. When the cell is first made, there is some irregularity in the action owing to molecular instability. This can be made to disappear, if both the wires are vibrated for a time. After these precautions are taken, results are obtained which are extraordinarily consistent.

Now if one of the two wires be continuously twisted, an increasing P.D. is induced during torsion between the acted and the unacted. This may be measured by the deflection of a sensitive galvanometer. Curves could thus be obtained with electromotive force, measured by the galvanometer deflection, as ordinate, and the time during which disturbance is kept up as abscissa. Such curves were directly obtained by the recording apparatus described in my previous paper. The wire was twisted at a uniform rate. The successive dots represent the completion of 360° . To keep the deflection within the scale, a megohm was interposed in the circuit. The resistance of the cell was about 5000 ohms. The absolute values of electromotive force corresponding to the galvanometer deflections were subsequently obtained by noting the effect of a known electromotive force.

2. Effect of Torsional Disturbance.

Most of the metals—exceptions presently to be described—become negative during molecular disturbance caused by torsion, i.e., the current through the *liquid* is from the acted to the unacted wire. As there is a considerable vagueness in the terms *positive* and *negative*, which has led to much confusion, I would name the acted wire as becoming *zincoïd* or Z , when under an external disturbance the current flows *through the electrolyte from the acted to the unacted wire*. Again, in certain cases the reverse is true; the current flows from the unacted to the acted wire; the acted wire will in that case be designated as *cuproïd* or C .

In fig. 12 is shown the effect of twist on Zn .

The induced electromotive variation is not due to twist as such, but to molecular disturbance induced during increasing twist. For if the wire be held stationary in the twisted position, the molecular disturbance with the attendant electromotive variation will gradually disappear. (Fig. 12.) Other evidences will be brought forward to show that the effect is simply due to the molecular disturbance, and not to the twist.

The wires used in the following experiments were from commercial specimens. The length was in every case about 9 cm., but the diameters were not the same.

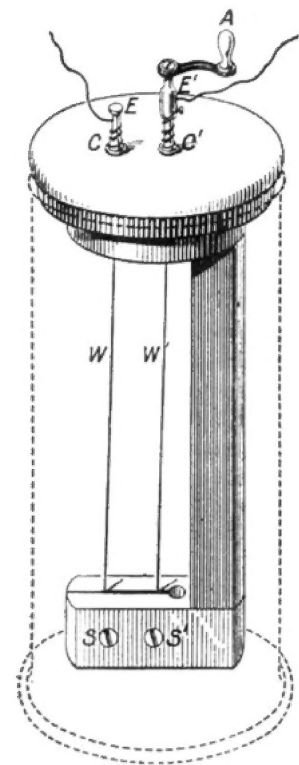


FIG. 11.—The Strain Cell.

If the conductivity variation under the stimulus of electric radiation and the electromotive variation under mechanical stimulus are but expressions of some molecular effect, we may expect the peculiarity of one kind of response reflected in the other. We shall presently see how closely the normal effects in the two classes resemble each other. Still more extraordinary are the similarities that exist even in abnormalities, several instances of which will be given later. I shall mention

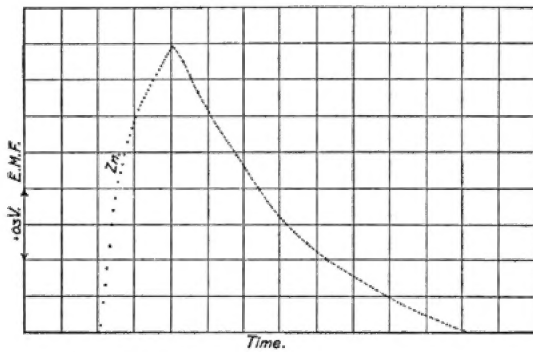


FIG. 12.—E.M. variation due to torsion of zinc wire. Successive dots in the ascending portion of the curve represent effect of rotation through 360°. The descending curve represents recovery.

here only one case. We have seen in experiments with electric radiation that substances sometimes fall into a sluggish molecular condition, when the responses almost disappear. Strong stimulation (induction shocks, &c.) or annealing is found to restore the sensitiveness. The same peculiarity is observed in the strain-cell. Lead, for example, specially on cold days, is apt to fall into a sluggish condition, when it becomes almost irresponsive. But it regains its sensitiveness after intense vibration or annealing.

All metals (including the noble metal Pt) when molecularly disturbed exhibit electromotive effect. The intensity of electromotive variation depends on the nature and physical condition of the substance. The intensity of effect does not, however, depend on the chemical activity of the substance, for the electromotive variation in the relatively inactive tin is greater than that of zinc. The electrolyte used in the following experiments is common tap-water, but similar effects are also obtained with distilled water.

3. *Self-recovery.*

It was said that the acted wire, usually speaking, becomes zincoid. This is not universally the case; there are substances which become cuproid under mechanical stimulus. I have previously said that electric radiation produces opposite effects on different substances; silver is often found to show an effect (increase of resistance) opposite to the generality of metals. It is very curious that silver is also often found to exhibit an opposite electromotive effect under twist, that is to say, the acted wire becomes C.

As long as the wire is not overstrained there is always a recovery. Observe the extremely regular recovery in the curve for Zn when the twisting was stopped. It will be noticed that the recovery is very rapid at first, but slow in the later part, and that the recovery is complete.

4. *Irreversible Molecular Effect of Twist.*

In the case of electric radiation or light, the impulses are of a vibrational nature, unlike the one-directioned mechanical twist used in the above experiments. To make the two sets of phenomena comparable, we should have the mechanical disturbance of a vibrational nature also. I therefore next tried to see what the effect would be of reversing the direction of the twist, and found that the induced electromotive force is independent of the direction of twist.

I next tried the effect of a complete torsional vibration. I twisted the wire suddenly through + 90°, then back to zero, then to - 90°, and again back to zero, the complete vibration being executed in half a second. It will be seen that under these conditions we have a mere vibration and no resultant twist. This gave rise to an electromotive variation, the magnitude of which simply depended, as will be shown later, on the amplitude of vibration. It did not matter in the least whether the vibration commenced with a right- or left-handed twist.

It may be stated here that similar electromotive variation is obtained by molecular disturbance produced by a tap.

I shall now describe the effect of mechanical stimulus of varying intensities and durations. The intensity may be varied by varying the amplitude of vibration. We shall also study the effect of a single stimulus, or the summated effect of rapidly succeeding stimuli.

A set of experiments on the effect of mechanical stimulus may thus be carried out parallel to those on the effect of radiation stimulus. It would then be instructive to compare the response-curves of mechanical and with those of radiation stimulus.

5. *Effect of a Single Stimulus.*

For studying the effect of mechanical stimulus, a voltaic element made of "tin" wire^[1] is very suitable. Normal responses are easily obtained after annealing. As has been said before, any other metal may be used; I have, in fact, obtained as good results with platinum. But the advantage of tin is that the electromotive variation is comparatively strong; under favourable conditions the electromotive variation obtained is as high as 0.4 volt; another advantage is that it shows very little fatigue. On freshly making the cell, signs may be exhibited of abnormal irritability; this is due to the fact that a stable molecular condition has not yet been reached; but a more settled state soon supervenes, and after that a succession of responses is obtained which are extraordinarily regular and consistent amongst themselves.

That the responses are due to molecular disturbance in the acted wire may be shown by the following experiment. The wire is clamped below; when the wire is subjected to torsional vibration, there is produced a strong molecular disturbance with the attendant electromotive variation. If the wire is now released from the clamp and vibration imparted as before, there would be no electromotive effect.

In fig. 13 is given a series of curves for different "intensities" of vibration. For want of space I have given a few only of each series. As a matter of fact, the succeeding series would have been mere repetitions of those which preceded. I have taken as many as 500 successive records, and each record is a mere duplicate of the rest. The substance does not exhibit any appreciable fatigue, especially if a period be allowed for complete recovery. It will be seen that the rise is quick, whereas the fall is comparatively slow, specially in the later part.

If sufficient time be allowed the recovery is complete. (In the curves given only 30 seconds were allowed, hence the recovery was not complete.) On the cessation of disturbance the electromotive variation gradually disappears, the wires returning to their original condition, after which similar cycles of operation may be repeated for any length of time.

In the case of molecular distortion due to electric radiation we met with similar instances of complete recovery. It was then shown that the effect was not primarily due to any chemical action, but was due to physical strain, the recovery taking place as it were by the release of strained molecular springs.

With strain cells, there is no permanent change; the stimulated wire returns exactly to its original condition on the cessation of disturbance.

In the borderland between physics and chemistry no sharp line of demarcation can be drawn between the two; such divisions are somewhat arbitrary. In the case of tin cell we have the two wires originally alike. When one wire is vibrated a difference of potential is observed between the strained and unstrained wires, the P.D. disappearing

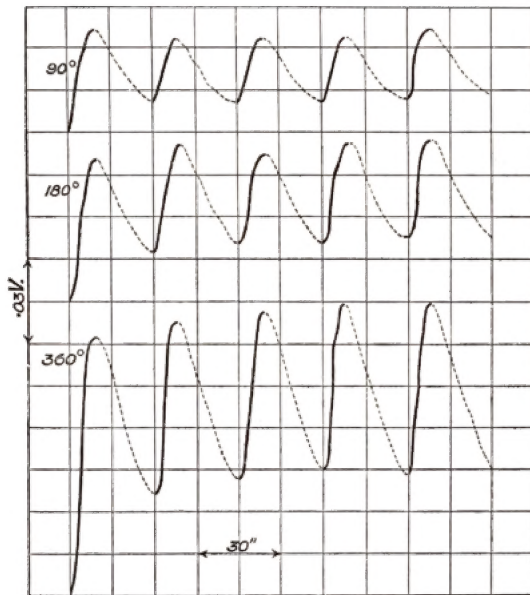


FIG. 13.—E.M. variation due to a single vibration through 90° , 180° , and 360° in a Tin cell. Period of vibration, 5". Thick lines represent effect of stimulus, dotted lines represent the recovery.

when the acted wire recovers from the strain. We may describe the same fact in chemical language by saying that owing to strain there is a tendency of the strained wire to become chemically more active (zinc-like), such tendency lasting only as long as it takes the wire to recover from the strained condition.

6. Increased Effect with Increasing Intensity of Vibration.

In fig. 13 are given the curves of response for single vibration, having amplitudes of 90° , 180° , and 360° , the period being 0.5 second. It will be noticed that the intensity of response increases with the energy of vibration.

7. Effect of Summation of Stimuli.

In the case of effect of rapidly succeeding flashes of electric radiation on Ag', it was shown (see fig. 14) that the partial effects were fused together and there was produced a limiting effect, kept balanced by the force of restitution. With rapidly succeeding mechanical stimuli, we again obtain an exactly similar result. Fig. 15 (a, b) shows the effect of continuous vibration on tin cell, with different intensities of vibration, the vibration-frequency being two in a second. The curve gradually rises and attains a maximum, at which position it is

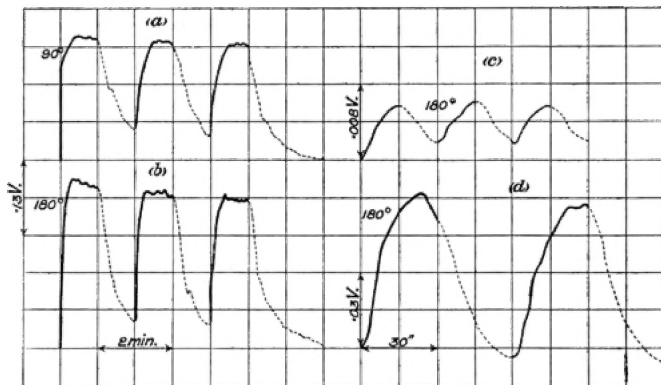


FIG. 14.—Effect of continuous vibration. (a) and (b) show effects on a Tin cell. In (c) the effect on the particular Silver cell; the sign of E.M. variation is opposite to that of Tin cell. (d) shows the effect on a Nickel cell.

held almost rigid as long as the disturbance is kept up. But on the stoppage of vibration there is an immediate recovery, and if sufficient time be allowed the recovery is complete, as seen in the last curve of the series. The disturbance was kept up for 1 minute, and the period of recovery allowed was also 1 minute. In this way I obtained a long-continued series of exactly similar curves, there being little fatigue; this is the case when a period of repose intervenes. But if the vibration is kept up without intermission signs of fatigue begin to appear, and the curve tends to fall. In some metals there may even be a reversal. Observe the flat top of the curve similar to that of Ag' under electric stimulus mentioned above. Also the effects of different intensities of vibration, as shown in (a) and (b).

In (d) is shown the effect of vibration on Ni. After reaching the maximum there is a tendency towards reversal. Ni also shows greater signs of fatigue.

In (c), fig. 14, is shown the interesting curve for a given piece of Ag. The effect is very much feebler, and curiously enough it gave an opposite response, the vibrated wire becoming cuproid. It was said that silver occupied a peculiar position as regards response to electric radiation,

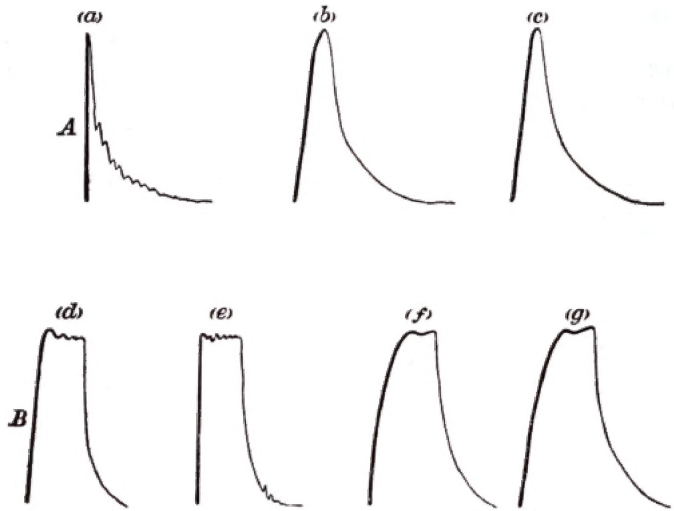


FIG. 15.

- A. Effect of stimulus of short duration.
- (a) Effect of electric radiation on Ag' (conductivity variation).
 - (b) „ light on HgBr (E.M. variation).
 - (c) „ mechanical vibration on Tin (E.M. variation).
- B. Effect of continued action of stimulus.
- (d) Effect of continued action of electric radiation on Ag' (conductivity variation).
 - (e) „ „ „ mechanical vibration on Tin (E.M. variation).
 - (f) „ „ „ light on AgBr E.M. variation).
 - (g) „ „ „ mechanical vibration on Nickel (E.M. variation).

sometimes responding in one, and again in an opposite manner, probably owing to its readiness to pass from one molecular condition to another, under slightly different external conditions. With mechanical vibration, too, I find silver exhibiting opposite electric variation, the acted wire becoming on different occasions either Z or C.

8. Reversal Effects.

Reversed Effect due to Sub-normal Stimulus.—Just like the negative effect (*i.e.*, opposite to the normal) often exhibited under electric radiation when the stimulus is below the critical intensity, so also it is found that a feeble mechanical stimulus often produces an effect opposite to the normal. Thus with strain cell made of lead, I found that whereas the acted wire became cuproid with an amplitude of vibration of 4°, the same wire when vibrated through 45° became zincoid. Thus in a Pb cell (50,000 ohms in circuit)

Amplitude of vibration.	Deflection.	Result.
4°	5 divisions to right	Acted wire C.
45°	70 „ left	„ Z.

This effect I have often noticed. It was too frequent to be accidental, but it did not occur invariably. On the occasions when it happened, this negative effect disappeared after continued vibration. Thus on taking a record of effect of continued vibration, there is produced a negative twitch, which is converted later into a positive deflection, just as in the curves of effect of light in fig. 17.

Reversal produced by Continued Stimulation.—After the maximum effect is reached, if the vibration is still continued, there is a tendency for the curve to descend to the neutral line. In the case of nickel I have even found the curve reversed, that is to say, there was a complete reversal of electromotive force.

I have described the various molecular effects produced by mechanical stimulus under varying conditions, and shown how very similar in every detail they are to the effects produced by electric radiation and light. How striking these similarities are, will be seen from the following tabular statement and comparison of different curves.

9. Molecular Effects common to Electric Radiation, Light, and Mechanical Vibration.

1. The molecular effect produced may be detected either by conductivity or electromotive variation methods.
2. Substances when not overstrained exhibit recovery, but the recovery is delayed when there is overstrain.
3. Response modified by previous history, and the influence of the surrounding conditions. Slight rise of temperature and annealing generally favourable to increased sensitiveness and quick recovery.
4. Under the action of electric radiation, light, and mechanical vibration, two opposite effects are exhibited; by the conductivity variation method this is seen in the diminution or increase of resistance; by the electromotive variation method we get positive or negative variation.
5. In the curve of response, in all the above cases, the ascending portion is abrupt, whereas the fall during recovery is at first rapid, then comparatively slow, the curve of recovery being thus convex to the abscissa.
6. Under rapidly succeeding stimuli, there is a fusion of individual effects; the curve rises to a maximum, when the force of restitution is kept balanced by the distorting force.
7. Sub-normal stimulus often produces a reverse effect. Too long-continued disturbance produces, or tends to produce, a reversal.
8. Under peculiar molecular modification, the response is of opposite sign to the normal. Continued stimulation converts abnormal to normal. The response curve may thus exhibit, at the beginning, a negative twitch followed by the normal positive.

A few curves are selected from experiments already described, and given below, in order to illustrate graphically the remarkable similarities of response to different kinds of stimulus. (See fig. 15.)

They show how essentially similar are the molecular effects produced, though the modes of stimulation and the methods used for the detection of effects produced are so different.

10. *Effect of Light Vibration balanced by Mechanical Vibration.*

I have hitherto spoken of the similarities of the radiation and mechanical strains, but have not yet said anything about their mutual relation.

It is known that in cases where electric radiation produces an increase of conductivity, mechanical vibration produces an opposite effect, *i.e.*, an increase of resistance. It thus appeared that we have here an exhibition of two opposite molecular effects. No definite conclusion could be drawn from this, however, as the increase of resistance may have been due to the mechanical separation of the conducting particles.

I then thought of trying the effects of light and mechanical vibration in producing electromotive variation in a strain cell. For this purpose I took a tin cell, and subjected one of the wires to the action of light and mechanical vibration alternately. The upper curve of fig. 16

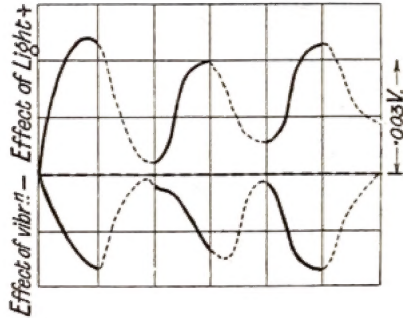
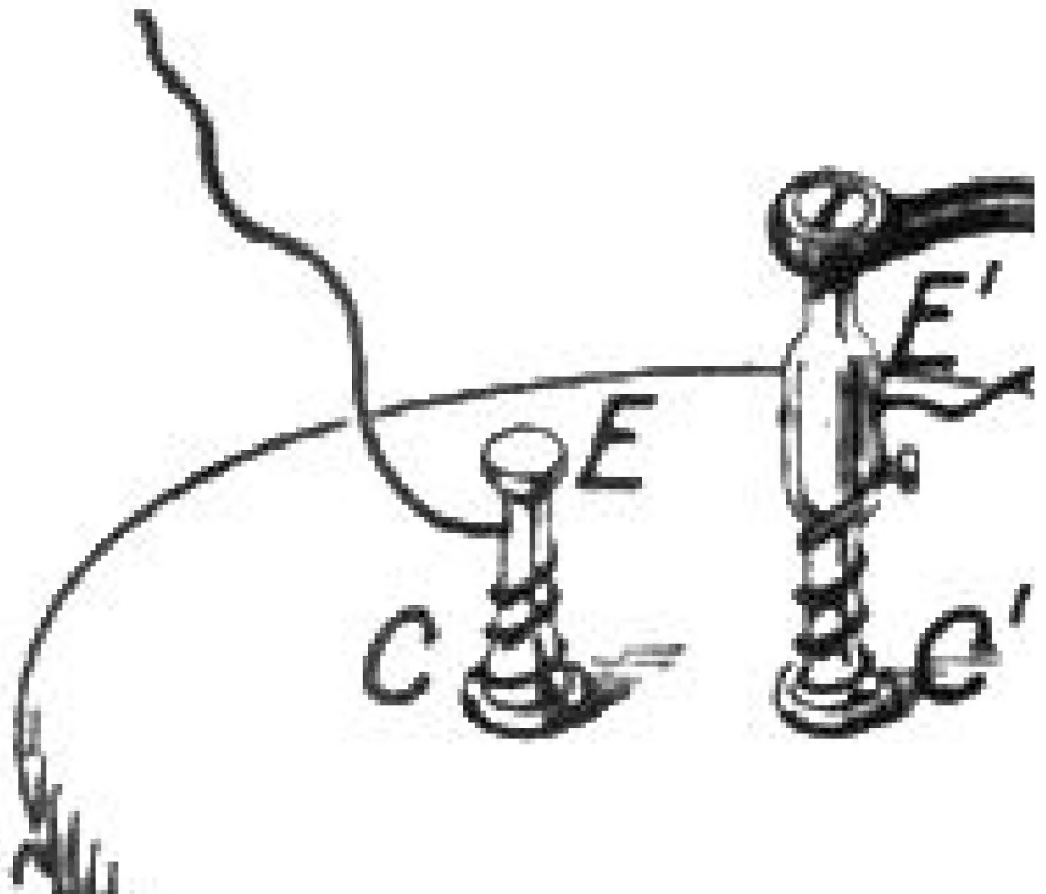


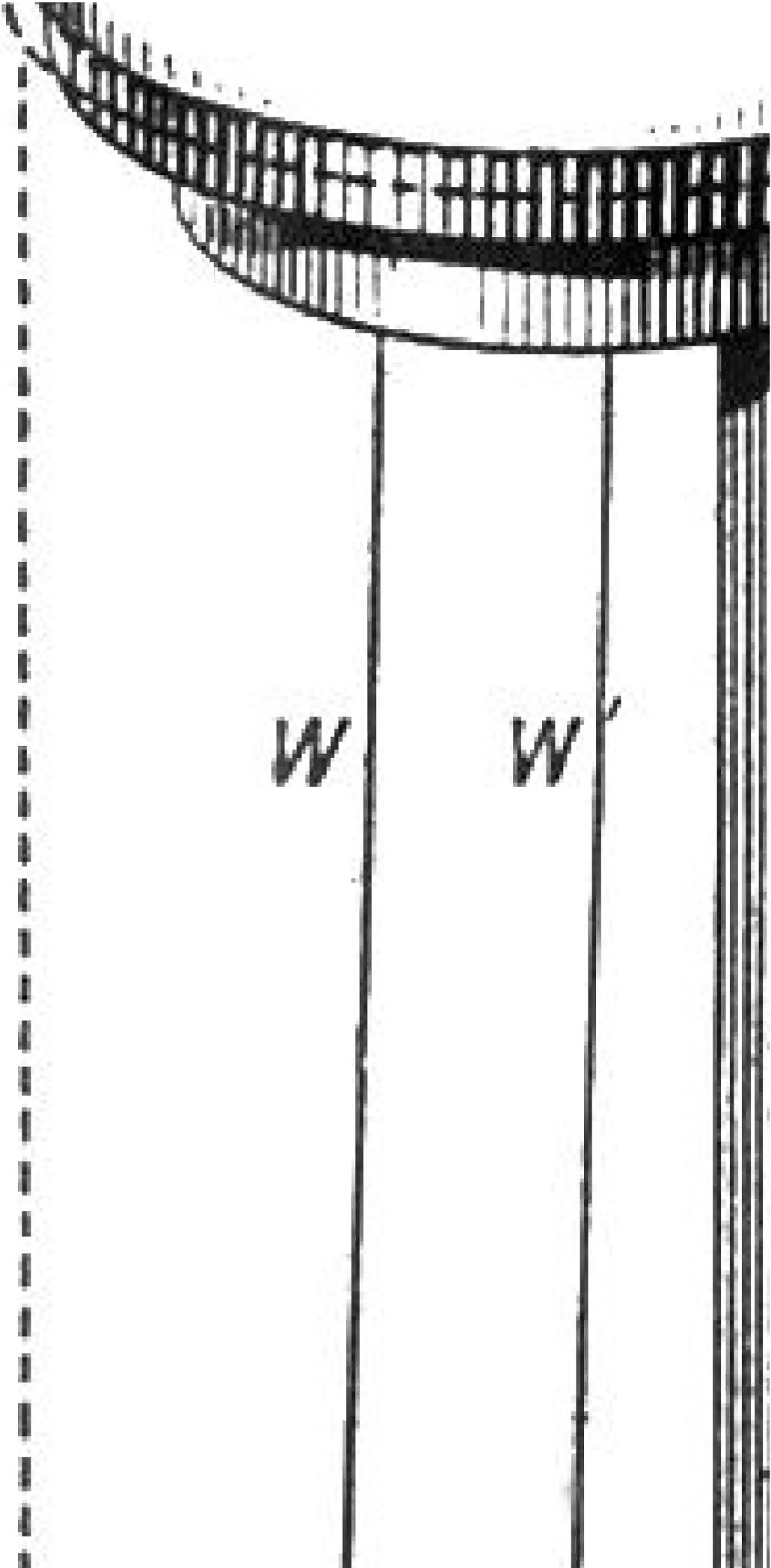
FIG. 16.—Effect of light and torsional vibration on a Tin cell. Light makes the acted wire cuproid, torsional vibration makes it zincoid.

shows the effect of light of a given intensity. It will be noticed that light makes the acted wire cuproid. But the action of mechanical vibration (see lower curve in same figure) makes the acted wire zincoid, and after several trials I found that a vibration with an amplitude of 3° produced a series of curves similar, but of opposite sign, to those produced by light. Thus mechanical vibration produced a molecular effect opposite to that of light.

I next allowed both the disturbing influences to act simultaneously on one of the wires, and the light action was then found to be exactly balanced by the action of mechanical vibration, an increase or diminution of either at once upsetting the balance.

The molecular effect of mechanical vibration thus appears, at least in the case of tin, to be opposite to that produced by light. This may be the case in general: the exception might be when one of the two stimuli is normal and the other sub-normal.





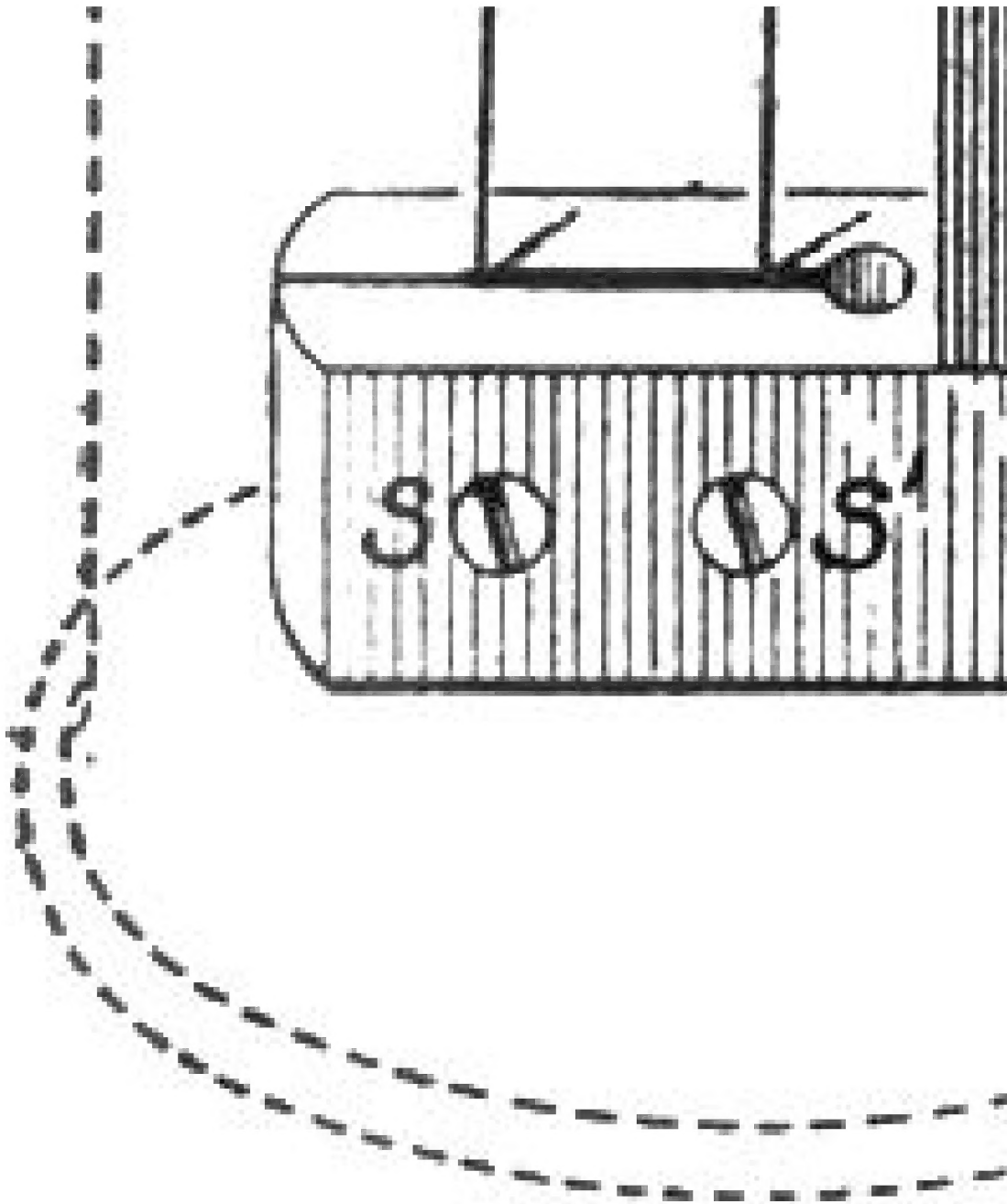


FIG. 1.—The Strain Cell.

1. By tin wire is meant what is sold as such, and used as electric fuse. It is a pliable alloy of tin and lead.

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